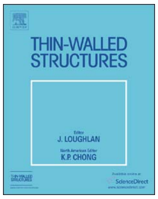
Thin-Walled Structures 107 (2016) 221–230

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws



Full length article

An analytical solution to lateral buckling control of subsea pipelines by distributed buoyancy sections

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ARTICLE INFO

Article history:
Received 21 January 2016
Received in revised form
3 June 2016
Accepted 8 June 2016

ABSTRACT

Lateral buckling is the primary buckling form of the subsea pipelines. A promising recent practice is to the distributed buoyancy sections to control the lateral buckling of subsea pipeline. In this study, an analytical solution is deduced for the lateral buckling of the pipeline with buoyancy sections in the entire design region. However, numerical difficulty was encountered during the solution of the design equations. To overcome this difficulty, we adopt a response surface method (RSM) for the solution of nonlinear equation system. A strategy of multi-response-surface is proposed by dividing the entire design region into several partial domains and establishing different kinds of response surfaces for each region. A framework for lateral buckling control of subsea pipelines using distributed buoyancy sections is presented. Several illustrative examples demonstrate that the proposed method has a high efficiency and accuracy in solving the problem of the lateral buckling control.

1. Introduction

Energy resources exploitation and transportation in deep water require long pipelines operated at high temperature and high pressure (HT/HP). The axial expansion caused by the increase in temperature and pressure may lead to lateral or upheaval buckling along the pipeline. Such uncontrolled global buckling would cause serious damage to the safety of the pipelines. Consequently, the industry preferred to restrain the global buckling problem by trenching and burying of pipeline. Trenching for the subsea pipelines is uncommon due to high cost in deep water [1,2]. Since the vertical resistance is larger than the lateral soil resistance against the pipeline, the lateral buckling becomes the primary buckling form and must be considered in the design [3]. On the positive side, lateral buckling can release the axial expansion effectively. Thus the solution to control the lateral buckles is considered to be more elegant than preventing them. Moreover, when the temperature and pressure increase further, the controlled lateral buckling is deemed to be the only economic solution [4,5]. Based on the concept of controlling the lateral buckling, the new design method is to install the buckle triggers along the pipeline route to initiate planned buckle [5]. The key challenge is to control the buckle behavior when exciting the lateral buckling. As a typical technique to initiate the lateral buckling under control, the use of distributed buoyancy sections have attracted more and more attention in the design of subsea pipelines [6]. This technique reduced the submerged weight of the pipeline by installing distributed buoyancy at the planned sites. It means that the buckle initiation force is reduced caused by the reduction in the lateral soil restraint. Finally, the likelihood of the buckle as planned is increased.

Many investigators have studied the pipeline buckling problem by experimental, numerical and analytical method in past decades [7,8]. Kerr [9,10] derived the analytical solution for the buckling problem of the thermal track modeled as an Euler beam. Based on Kerr's study, Hobbs [11] investigated the buckling problem of the ideal straight heated pipeline on the rigid seabed and obtained the concise analytical solution of the buckling behavior. The studies of Kerr and Hobbs laid the foundation of theoretical analysis of the global buckling of pipelines. When using the buoyancy sections, the lateral resistance along the pipeline is no longer uniform, and Hobbs's solution is no longer applicable. The buoyancy sections can be regarded as a means of initial imperfections. Antunes [12] presented the governing equations and the boundary conditions for the lateral buckling of subsea pipelines with distributed buoyancy sections. In his study, the length of the buoyancy section and the submerged weight ratio between the buoyancy section region and other region were chosen as the design parameters. However, the solution was not given in his paper. A number of investigators analyzed the global buckling of a pipeline on a rigid seabed with the initial imperfections on basis of the studies of Kerr

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http://dx.doi.org/10.1016/j.tws.2016.06.003

and Hobbs. The influence of the initial imperfections on the global buckling behavior is investigated in their works [13–16]. Ralf Peek [17,18] investigated the effect of the flotation on the pipeline buckling form, and found that the flotation will cause the pipe to buckle laterally not upwards on the flat seabed. A scaling technique was proposed by the author to calculate lateral buckling behavior of the inelastic pipeline quickly.

The analysis of pipeline buckling by finite element method (FEM) and numerical match method has been paid more attentions [3,19]. Zeng [20] studied the upheaval buckling behavior of a buried pipe by dimensional analysis and FE analysis. The approximation formula of critical axial force for imperfections was further developed through numeric fitting in his paper. Furthermore, the influence of the soil on the pipeline buckling behavior has also attracted the researchers' attention in recent years [21,22].

However, there is less theoretical analysis for the pipeline lateral buckling with distributed buoyancy sections at present, which hinders the cognition on the physical essence.

This paper deduces an analytical solution for the lateral buckling of the subsea pipelines with distributed buoyancy sections. In the analytical solution, the length ratio β between the buoyancy section region and the buckling region and the submerged weight ratio γ between the buoyancy section region and other region are chosen as the design parameters. Benefiting from the dimensionless design parameters with the values from 0 to 1, a closed design region is obtained. This analytical solution, covering the entire design region, is no longer limited to the upper bound of the distributed buoyancy sections length. In order to overcome the numerical instability of the solution of nonlinear equation system and to improve the calculation efficiency, the relationship between the buckling behavior and the design parameters of distributed buoyancy sections is modeled by using RSM based on the analytical solution. RSM consists of a set of mathematical and statistical techniques introduced by Box and Wilson in 1951 [23]. This method can be used to predict an approximate response for the known variables by establish a relationship between them. The examples demonstrate the efficiency and accuracy of the proposed RSM based solution.

2. Analytical model for lateral buckling of a pipeline with buoyancy sections

Kerr [10] and Hobbs [11] deduced the analytical solutions for lateral buckling of track-beam and pipelines, respectively. In Hobbs's analytical model, the pipeline was assumed to be placed on rigid seabed. The axial compression force P_0 in the pipeline before buckling, the axial compression force P in the buckling region, the axial coefficient of friction μ_A and the lateral coefficient of friction μ_L are assumed to be constants in their solution. The lateral buckling configuration and the force distribution are shown in Fig. 1, in which the pipeline is divided into lateral buckling region and axial slip region. The axial and lateral displacements are 0 at the point $x=L_0$, defined as the virtual anchor point.

In this paper, we adopt the same assumptions with the referred authors to derive the analytical solution of the symmetrical lateral buckling modes for the pipeline with buoyancy sections. In this study only the reducing in the submerged weight is considered and the contribution to the stiffness of the buoyancy sections is neglected. According to the symmetry of the lateral buckling configuration, half of the model is to be analyzed in the following sections. Because of the design of buoyancy sections, the submerged weight per unit of length along the pipeline is nonuniform, with W_{sb} in the region of the buoyancy section and W_s in other regions. The submerged weight ratio γ between W_{sb} and W_s, the length ratio β between the buoyancy section region and the buckling region are chosen as the design parameters in this paper. And the length of distributed buoyancy sections are assumed to be smaller than the buckle lobe, so a closed design region $0 \le \gamma \le 1$ and $0 \le \beta \le 1$ is obtained.

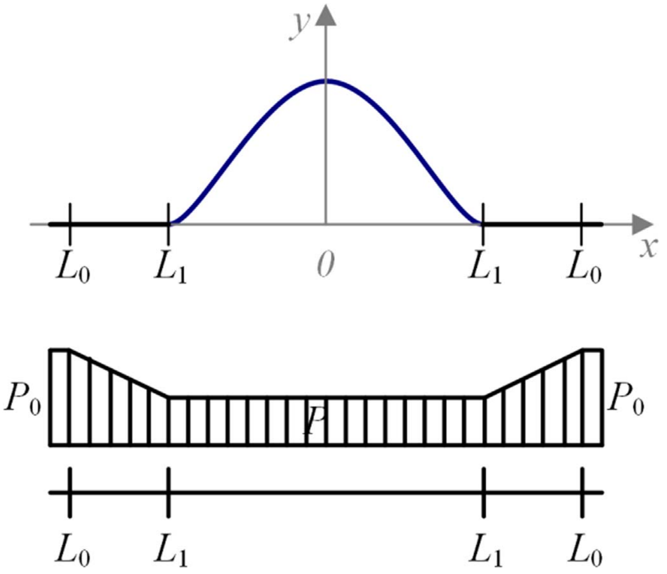

Fig. 1. Classical lateral buckling configuration and the axial force distribution.

Previous researches indicated the symmetrical modes (mode 1 and mode 3) are more dangerous than the antisymmetrical modes (mode 2 and mode 4) [10,11].

2.1. Analysis for lateral buckling mode 1 of problem

The general lateral buckling configuration of mode 1 is shown in Fig. 2. The distributed buoyancy sections region is from 0 to L_B in which the axial displacement u, lateral displacements v and Lagrangian strain ε are identified by the subscripts B. The buckle lobe without distributed buoyancy sections is from L_B to L_1 in which the axial displacement u, lateral displacement v and Lagrangian strain ε are identified by the subscripts 1. The axial sliding region is from L_1 to L_0 in which the axial displacement u and Lagrangian strain ε are identified by the subscripts 2. The point at L_0 is considered as the virtual anchor point.

According to the equilibrium of forces and moments, the following equations are obtained:

$$EIv_B'''' + Pv_B'' = -\gamma\mu_L W_s \quad 0 \le x \le L_B \tag{1}$$

$$EIv_1'''' + Pv_1'' = -\mu_L W_s \quad L_B < x \le L_1 \tag{2}$$

$$P_0 - EA\varepsilon_B = P \quad 0 \le x \le L_B \tag{3}$$

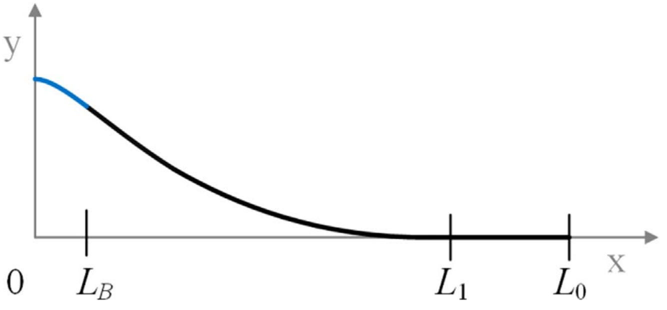

Fig. 2. Lateral buckling configuration-mode1.